COINCIDENCE DETECTION IN NEURONS WITH IN VIVO-LIKE SYNAPTIC ACTIVITY

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ABSTRACT
Neuronal synchronization is ubiquitous in the nervous system, yet its functional role for information processing is still unclear. Because of the leak current, two input spikes are more likely to make a postsynaptic neuron fire when they are synchronous. This coincidence detection property has been demonstrated in vivo for thalamocortical processing [1], but the theory of coincidence detection in neurons with in vivo-like synaptic activity is still sparse. We estimated the extra probability for a noisy neuron to fire a spike in response to two synchronous input spikes compared to two distant spikes. Using a simple probabilistic approach, we were able to quantify this extra probability for spiking models as a function of the background noise and the shape of postsynaptic potentials. Our predictions agreed well with numerical simulations. We found that neurons act as coincidence detectors when excitation and inhibition are balanced, as in cortical neurons in vivo, but not in the mean-driven regime. In the balanced regime, coincident spikes can be several times more efficient than distant spikes in realistic situations. We conclude that in cortical neurons, the relative timing of presynaptic spikes has a major impact on postsynaptic firing.

KEY WORDS
Synchrony, coincidence detection, spiking neuron models, balanced regime.

1. Introduction

The impact of synchronous inputs on the postsynaptic neurons has been studied in several experimental studies, in particular in the early visual system [1]. However, coincidence detection has not been clearly quantified in neuron models. Specifically, the conditions under which a neuron acts as an integrator or a coincidence detector are unclear. Here, we present a simple theoretical framework to quantify the coincidence detection properties of general neuron models. We show that coincidence detection is modulated by background synaptic activity and depends critically on the mean background input. When the mean is below the threshold (balanced regime), the neuron acts as a coincidence detector, while when it is above the threshold (mean-driven regime), the neuron acts as an integrator. The balance between excitation and inhibition is therefore a necessary condition for the neuron to be able to detect synchronous events among its inputs. We also obtained an analytical expression for the increase in output firing rate as a function of the background noise and the shape of the postsynaptic potentials, which agrees with numerical results. These results show that a neuron in the balanced regime is extremely sensitive to synchronous events, even among a very small number of synapses.

2. Theory

We consider a spiking neuron model with membrane potential $V(t)$ and threshold θ receiving stochastic in vivo-like synaptic activity $N(t)$ and k synchronous postsynaptic potentials $PSP(t)$: $V(t) = N(t) + k\,PSP(t)$. The mean of $N(t)$ is assumed to be below the threshold, so that the neuron is in the balanced regime. We estimate the firing probability of the neuron as a function of the background noise and the shape of postsynaptic potentials, with the approximation that the fluctuations of the background noise are slow compared to the time course of the PSPs. We find that this probability can be estimated directly from the stationary distribution of the noise. With w the maximum of the postsynaptic potentials, the firing probability $F(w)$ equals the probability that $\theta - kw \leq N \leq \theta$, with N the value of the noise right before the synchronous PSPs.
Figure 1 illustrates the fact that F(2w)>2F(w) in the balanced regime, that is, that two synchronous input spikes are more effective than two distant ones. Although the noise distribution is Gaussian in this illustration, our framework requires no assumption about it.

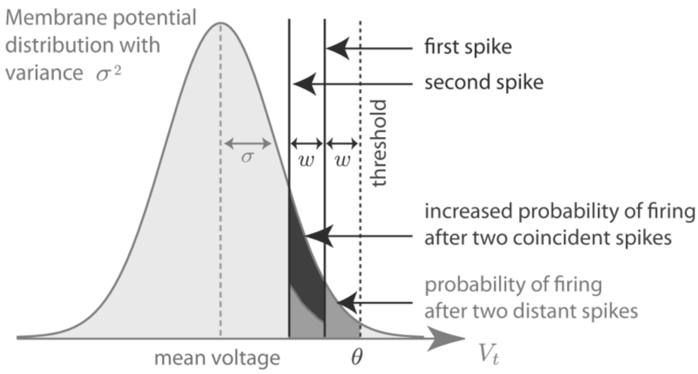

Figure 1. Membrane potential distribution with an illustration of the coincidence detection effect. The output firing probability after two asynchronous spikes is the light area, and the extra firing probability after two synchronous spikes is the dark area. This extra probability is strictly positive, showing the coincidence detection effect.

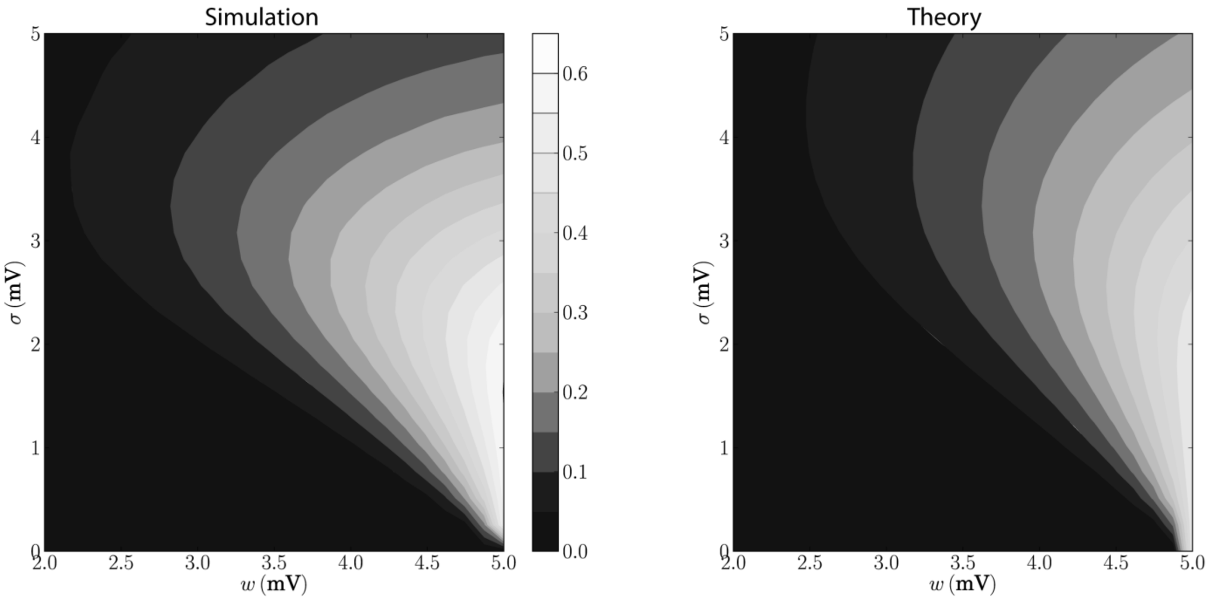

Figure 2. Coincidence sensitivity as a function of the standard deviation of the background noise and the size of the postsynaptic potentials (left: numerical simulations; right: theoretical predictions).

3. Results

3.1 Coincidence sensitivity

In order to quantify the coincidence detection property of neurons with in vivo-like synaptic activity, we define the coincidence sensitivity $S(w)$ as the extra probability for a neuron to fire a spike in response to two synchronous input spikes compared to two distant spikes. This quantity also depends on the distribution of the background noise. In our theoretical approach, we assume that noise fluctuations are slow, which implies that $S(w) = F(2w) - 2F(w)$. We found numerically that this simple formula is still valid for faster fluctuations. It follows that two synchronous spikes can be several times more efficient in making the postsynaptic neuron fire than two asynchronous spikes.
Figure 2 shows the coincidence sensitivity as a function of w and σ (standard deviation of the background noise N(t)), for both the theory and numerical simulations obtained with a leaky integrate-and-fire model and an Ornstein-Uhlenbeck background noise.

3.2 Distributed synchrony

We applied these results to estimate the output firing rate of a neuron driven by many excitatory and inhibitory synaptic inputs among which a very small fraction is synchronous. In Figure 3, synchrony events occur at a rate of 0 to 40 Hz. Each event consists in the synchronous firing of up to 40 excitatory input neurons (among 4,000). The synaptic weights are chosen so that the neuron is in the balanced regime. It appears that the neuron response is very sensitive to synchrony, even when the input firing rates are fixed: the output firing rate can be about five times higher than when there is no synchrony. This result holds as long as the timescale of correlations is smaller than the integration time constant.

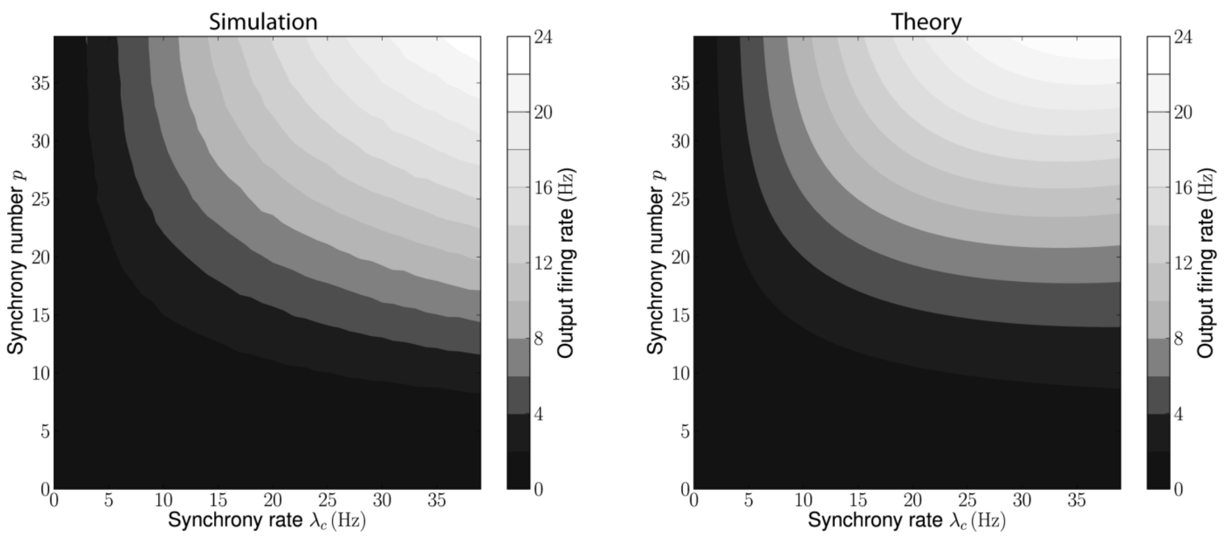

Figure 3. Distributed synchrony. Output firing rate of the postsynaptic neuron as a function of the rate of synchronous events and the number of synchronous synapses at each synchronous event (left: numerical simulations; right: theoretical predictions).

4. Conclusion

Our results show that in cortical neurons, which are driven by balanced excitatory and inhibitory inputs, the relative timing of presynaptic spikes has a major impact on postsynaptic firing. The balance between excitation and inhibition is a necessary condition for the neuron to act as a coincidence detector: when excitation exceeds inhibition, the neuron acts as an integrator. Finally, our theoretical approach provides analytical formulae to quantify coincidence detection in neuron models as a function of the distribution of background activity and the shape of postsynaptic potentials.

Acknowledgements

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References

[1] WM. Usrey, JM. Alonso & RC. Reid (2000), Synaptic interactions between thalamic inputs to simple cells in cat visual cortex, *Journal of Neuroscience 20*(14)